REPORT

SP 4 FoU Snøskred

ANNUAL REPORT 2018

DOC.NO. 20170131-11-R
REV.NO. 0 / 2018-12-21

NORWEGIAN GEOTECHNICAL INSTITUTE
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Project

Project title:	SP 4 FoU Snøskred
Document title:	Annual Report 2018
Document no.:	20170131-11-R
Date:	2018-12-21
Revision no. /rev. date:	0 /

Client

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Contract reference:	Letter from NVE to NGI 2017-11-30

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CERTIFIED BY BSI
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Summary

In the second year of the present three-year project period, core and/or long-term activities were continued:

- experiments at Ryggfonn and maintenance of the site,
- infrasound monitoring along State Road 15 between Fonnbu and Ryggfonn,
- continuous video monitoring of the deflection dam at Gudvangen,
- surveys and analyses of interesting avalanche events, and
- leadership and administration of the Circum-Arctic Slushflow Network.

Several adjustments to the workplan had to be made due to maternity leaves and illnesses of several project participants:

- Activities had to be reduced in WPs 3 (slushflows) and 5 (wind fields and snow transport in mountainous terrain).
- Readying StatPack, the new probabilistic system for local avalanche forecasting, for real-world testing in the winter 2019, required a substantial effort.
- Several existing numerical models were extended and/or improved in WP 1.
- In WP 5, work on avalanche release probability was initiated earlier than originally planned.

Some highlights of results obtained in 2018 are the following:

- Only one (spontaneous) avalanche occurred at Ryggfonn.
- Still more information on the scaling behavior of run-out distance and avalanche speed could, however, be gained by comparing data from Ryggfonn to observations and measurements from other sites. Using these results, rough estimates of the return period of an observed event in a path can be made from its run-out angle and the path steepness—quantities that can be readily observed.
- By similar statistical methods, correlations between the path steepness, the run-out angle of the powder-snow part and the corresponding probability were proposed.
- Significant improvements in StatPack concern
  - enhancements to the release probability module,
  - the downslope routing of “avalanches” from each single cell, and
  - the calculation of the hit probability in the run-out area.
- Collaboration with Japanese researchers opened for testing Voellmy-type run-out models against slushflows that were detected and tracked along their path through a network of seismometers.
- Simple mechanical analyses of the observations during the survey of the 2017 avalanche in Rigopiano, Italy gave useful insights:
  - Trimlines allow to constrain the front and tail velocity.
  - The avalanche lost relatively little energy destroying ~10 ha of forest.
  - Entrainment of much snow and tree debris slowed the avalanche front down.
  - The force required for pushing the ruins of the hotel over tens of meters is compatible with the avalanche pressure expected at the hotel location.

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Review and reference page

1 Overview and administrative aspects

1.1 Project goals in 2018

The project goals and deliverables for 2018, as originally established in the project proposal, are shown in Table 1. As explained in Sec. 1.2, bottlenecks in the availability of suitable project members compelled us to make changes to the workplan and accordingly to the list of deliverables. These changes will be presented in detail in the sections on the respective work packages. Sections 2.2 and 2.3 of the present report constitute Deliverables D1.3 and D1.4, respectively, in addition to the papers listed in Sec. 1.4.

Table 1 Summary of project goals 2018, based on the project proposal

WP 1	Maintenance of full-scale test site Ryggfonn and research station Fonnbu (2017–2019) Full-scale experiments at Ryggfonn with artificial release (2017–2019) Deliverable D1.3 – annual report/paper on experiments Contribution to development of dynamical models (2017–2019) Deliverabe D1.4 – annual report/paper on model development
WP 2	StatPack: testing and introduction into operational local avalanche forecasting (continued from 2017) Deliverable D2.1 – Report/paper on the use of StatPack Deliverable D2.2 – Introductory course and user manual for StatPack Impact of mitigation measures on land-use planning (2018) Deliverable D2.3 – Report/paper on case studies of the effect of mitigation measures on land-use planning
WP 3	Snow-cover simulation (2017–2018) Methodology for forecasting of slushflow danger (2018–2019) Test of Voellmy-type model in slushflows (2017–2018) Deliverable D3.1 – Recommendations for use and/or further development of Voellmy-type models for slushflows Circum-Arctic Slushflow Research Network (2017–2019)
WP 4	Investigation of interesting snow-avalanche events (2017–2019) Deliverable D4.2 – annual report/publication on investigated avalanches Detection of snow avalanches by means of infrasound (2017–2018) Deliverable D4.4 – Report/paper on results from infrasound experiment
WP 5	Wind field in mountain topography (continued from 2017) Deliverable D5.1 – Report/paper on Winstral model applied to Norwegian mountain areas Estimation of drift-snow quantity under known wind conditions (2018–2019) Deliverable D5.3 – Report/paper for estimating drifting snow in complex mountain terrain Quantification of avalanche release probability (2018–2019) Deliverable D5.2 – Report/paper on observed and forecasted release probabilities

1.2 Use of human and financial resources

2018 was a challenging year for FoU Snøskred because several project participants were absent due to maternal leave or illness, and others were more occupied in other projects than anticipated. Since in many cases, specific knowledge and competences cannot easily and immediately be supplied by other researchers, we chose to postpone work in the most affected work packages 3 and 5 and use the corresponding resources in WP 1 for model development and in WP 2 for further testing and improvement of StatPack.

Table 2 Contributors to the project in 2018, listed alphabetically

Name	WP	Topic
Hedda Breien	0	Webpage content
Marte F. Busengdal (UiO)	1	Ryggfonn experiment
Peter Gauer	1 5	Leader WP 1, Ryggfonn experiments, data analysis Tests of WindSim
Kjersti Gisnås	5	Climate analysis, WindSim
Sylfest Glimsdal	2 5	Leader WP 2, implementation of StatPack Tests of WindSim
Øyvind A. Høydal	1	Ryggfonn experiment
Dieter Issler	0 1 2 4	Project leader Model development Quality assurance WP 2 Analysis of observed avalanche events
Christian Jaedicke	2 3	Quality assurance WP 2 (fuzzy rules) Leader WP 3, CASN
Krister Kristensen	1 4	Ryggfonn maintenance and experiment Infrasound tests
Erik Lied	1	Maintenance of the Ryggfonn measurement system
Galina Ragulina	2 5	Fuzzy rules in StatPack, testing of the release module in StatPack Testing of NGI-Klima
Frode Sandersen	4	Leader WP 4
Helge C. Smebye	1	Ryggfonn – experiment and LiDaR data analysis
Kjetil Sverdrup-Thygeson	1	Model implementation in GIS
Marco Uzielli	2	Statistical and fuzzy methods in StatPack

Table 3 Budgeted and actual allocation of resources per work package in 2017 (all amounts in kNOK)

	WP 0	WP 1	WP 2	WP 3	WP 4	WP 5	Sum
Budget 2018	350	1 100	550	200	500	300	3 000
Used 2018	301	1 533	657	41	426	175	3 133
Difference	–49	+433	+107	–159	–74	–125	+133

1.3 Summary of results

Once more, WP 1 saw a winter pass without clear opportunities for successful release of avalanches in Ryggfonn. During preparations for a final attempt, an avalanche released spontaneously only minutes before the radar and other devices were ready. Further work in WP 1 (Gauer, 2018a; McClung and Gauer, 2018) completed the analysis of experimental data that was initiated earlier. In addition, observations on the runout of the powder part of avalanches were collected and analyzed.

Modeling work within WP 1 implemented an improved formulation of the extra flow resistance in a forest stand in MoT-Voellmy and developed several GIS tools based on different modules of NAKSIN, the new system for producing avalanche hazard indication maps. Furthermore, WP 1 supported work in other NGI research projects on erosion and on powder-snow avalanches and turbidity currents.

The work in WP 2 was focused on testing and improving StatPack, the new tool for probabilistic avalanche hazard assessment. The fuzzy rules for calculating release probabilities were reviewed and adjusted. A significant improvement resulted from considering all cells within a release area collectively in the computation of run-out probabilities, but the need for further work on the distribution function for run-out distance has been recognized. Nevertheless, StatPack can be used operationally in local avalanche forecasting in the winter 2019.

Due to scarcity of human resources, work in WP 3 on slushflows was halted temporarily, but will be resumed in 2019. Work in WP 5 was also reduced significantly relative to the original plan due to scarcity of personnel, but several tests of WindSim were run, tools for retrieving and analyzing climate and weather data from SeNorge.no and met.no were developed, and theoretical work on avalanche release probability (including the effect of forest) was carried out and published.

In the framework of WP 4, a relatively small avalanche that destroyed a cabin in Oppdal in January 2018 was investigated and described in a report. The report on the survey of the deadly Rigopiano avalanche in January 2017 was finalized and a second report analyzing the dynamics of this avalanche event written. At Strynefjellet, unusually few avalanches occurred in the winter 2018 so that the joint project with SVV and Wyssen Norge AS on infrasound-based avalanche detection could not collect much useful data. Moreover, the system was out of order during extended periods, which prompted Wyssen Norge AS to offer another test season during the winter 2019 without additional charges.

Project administration (WP 0) proceeded as anticipated. Dissemination of project results was above the level of 2017 in terms of the number of published articles and reports, most of which were produced by WP 1. A manuscript on results from WP 2 is nearing completion, however. A new project webpage is under development and is expected to come online in January 2019.

1.4 Dissemination

(Underlined names refer to project participants)

Presentations at conferences, symposia and meetings

Gauer, P., Estimates on the reach of the powder part of avalanches. Poster at International Snow Science Workshop 2018, Innsbruck, Austria

Gauer, P., Avalanche probability: slab release and the effect of forest cover. Poster at International Snow Science Workshop 2018, Innsbruck, Austria

Glimsdal, S., G. Ragulina, M. Uzielli and C. Jaedicke. Probabilistic evaluation of snow avalanche runout. PiCO presentation at the EGU General Assembly 2018, Vienna, April 2018

Issler, D., P. Gauer, K. Gleditsch Gisnås and U. Domaas, The effect of forest on avalanche susceptibility maps — Norway. Oral presentation at the IGS Symposium Cryosphere and Biosphere, Kyōto, Japan, 2018-03-16

Nishimura, K., C. Pérez-Guillén, Y. Ito, S. Yamaguchi, Y. Saito, D. Issler and J.-T. Fischer (2018). Studies on the snow avalanche dynamics by the full-scale experiments. Poster at Intl. Snow Science Workshop, Innsbruck, Austria

Pérez-Guillén, C., K. Tsunematsu, K. Nishimura and D. Issler (2018). Avalanches on Mt. Fuji, Japan: seismic detection and tracking combined with numerical simulations. Oral presentation by C. Pérez-Guillén at Intl. Snow Science Workshop, Innsbruck, Austria

Publications

Faug, T., B. Turnbull and P. Gauer (2018). Looking beyond the powder/dense flow avalanche dichotomy. *J. Geophys. Res.: Earth Surf.* **123**, 1183–1186.

Gauer, P. (2018a). Considerations on scaling behavior in avalanche flow along cycloidal and parabolic tracks. *Cold Reg. Sci. Technol.* **151**, 34–46.

Gauer, P. (2018b). Estimates on the reach of the powder part of avalanches. In: Proc. Intl. Snow Science Workshop 2018, Innsbruck, Austria. International Snow Science Workshop, pp. 815–819, URL http://arc.lib.montana.edu/snow-science/objects/ISSW2018_P08.23.pdf

Gauer, P. (2018c), Avalanche probability: slab release and the effect of forest cover. In: Proc. Intl. Snow Science Workshop 2018, Innsbruck, Austria. Intl. Snow Science Workshop, pp. 76–83, URL http://arc.lib.montana.edu/snow-science/objects/ISSW2018_P01.13.pdf

McClung, D. M. and P. Gauer (2018). Maximum frontal speeds, alpha angles and deposit volumes of flowing snow avalanches. *Cold Reg. Sci. Technol.* **153**, 78–85.

Nishimura, K., C. Pérez-Guillén, Y. Ito, S. Yamaguchi, Y. Saito, D. Issler and J.-T. Fischer (2018). Studies on the snow avalanche dynamics by the full-scale experiments. *In:* Proc. Intl. Snow Science Workshop 2018, Innsbruck, Austria. Intl. Snow

Science Workshop, pp. 50–53, URL http://arc.lib.montana.edu/snow-science/objects/ISSW2018_P01.8.pdf

Pérez-Guillén, C., K. Tsunematsu, K. Nishimura and D. Issler (2018). Avalanches on Mt. Fuji, Japan: seismic detection and tracking combined with numerical simulations. *In:* Proc. Intl. Snow Science Workshop 2018, Innsbruck, Austria. Intl. Snow Science Workshop, pp. 11–15, http://arc.lib.montana.edu/snow-science/objects/ISSW2018_O01.3.pdf

Reports

Issler, D., Field Survey of the 2017 Rigopiano Avalanche. NGI Technical Note 20170131-02-TN

Issler, D., Tertialrapport 2018-1. NGI Technical Note 20170131-07-TN [in Norwegian].

Issler, D., Tertialrapport 2018-2. NGI Technical Note 20170131-09-TN [in Norwegian].

Issler, D. and Z. Liu, Design Alternatives for a Tool for Probabilistic Run-Out Calculations with MoT-Voellmy. NGI Technical Note 20170131-10-TN

Issler, D., P. Gauer, S. Glimsdal, C. Jaedicke and F. Sandersen, SP 4 FoU Snøskred – Annual Report 2018. NGI Report 20170131-11-R [present document]

Web site

Work on setting up a new webpage under https://www.ngi.no/eng/Projects/Avalanche-research for the period 2017–2019 was delayed once more, this time due to prolonged sick leave of a project participant, but was started towards the end of the year and has progressed well. It is expected to come online in the winter 2019.

The new webpage 2017–2019 will be accessible from the home page of SP 4 FoU Snøskred, from where the content from the period 2014–2016 will continue to be available. The new pages will summarize the goals, methods, and main results in each work package; there will also be links to all relevant documents like reports and journal publications.

2 WP 1 – Full-scale experiments at Ryggfonn and model development

2.1 Maintenance of the full-scale avalanche test site Ryggfonn

Under this task, necessary repairs and updating of the data acquisition system at the Ryggfonn avalanche test site (Stryn municipality, Sogn og Fjordane county, western Norway) were carried out so that the site is ready for the winter season 2018/2019.

Due to budgetary restrictions, for several years this work has been kept at the lowest possible level that keeps the site operational. The need for more thorough maintenance, including replacement of aging parts, is becoming increasingly evident. In 2019, we will therefore develop a plan for preventive maintenance that will ensure the site to remain functional and capable of delivering useful measurements for the design of mitigation measures and model development.

2.2 Experimental results from the full-scale test site Ryggfonn

This section constitutes Deliverable D1.3.

2.2.1 Avalanche releases

One spontaneous avalanche of size 2 to 3 (on the EAWS avalanche size scale) occurred during the winter 2017/2018. The avalanche occurred during preparation of an avalanche release campaign on 2018-04-19. Figure 1 shows a photo of the deposit and Figure 2 presents an example of data recorded during this event. The average front velocity between the pylon and the concrete wedge was about 22 m s^{-1}, and between the concrete wedge and mast 2 it was about 18 m s^{-1}. At mast 2, the front velocity is estimated at approximately 8 m s^{-1}.

Otherwise, no natural avalanches were recorded, nor occurred a weather situation that held promise for artificially releasing a sizeable avalanche and obtaining good-quality measurements.

2.2.2 Experiences in snow scanning with Optech Ilris LiDaR

NGI's full-scale avalanche research site at Ryggfonn is heavily instrumented, and LiDaR scanning of the avalanche path just before and after an avalanche is an important part of the data collection protocol during a measurement campaign. The distance from the scanner position to the avalanche path ranges from 1500 m to 2500 m. Measurement campaigns are contingent on the presence of sufficient quantities of erodible snow in the avalanche path and clear weather so that the scanner crew can safely be flown to the summit of Sætreskarsfjellet by helicopter. Figure 3 presents a map of the test area and Figure 4 is a photo of the avalanche path.

Figure 1 Spontaneous avalanche 20180419 in the lower part of the track seen from the dam

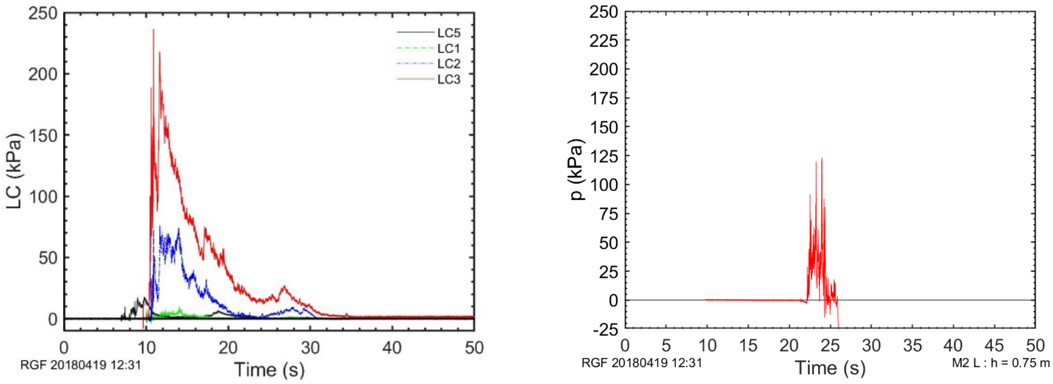

Figure 2 Natural avalanche 20180419: Pressure measurements at the pylon and concrete wedge (left) and mast 2 (right).

In 2012, NGI purchased an Optech Ilris LR scanner after evaluating (borrowed) scanners from Riegl and Optech in 2011. The decisive point in favour of the Optech model was its higher resolution and the concomitant wider range of potential use in NGI's consulting and research work. However, the Optech Ilris scanner has until now not created a single successful scan of a snow surface in direct sunlight.

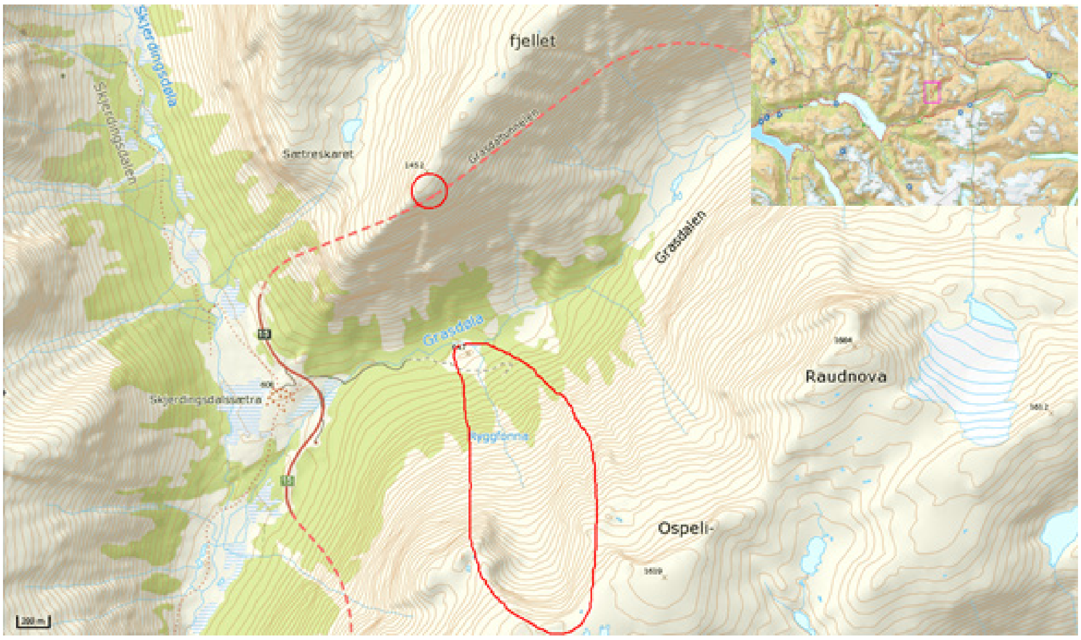

Figure 3 Map of the Ryggfonn research area. The avalanche path is indicated as a red polygon, and the scanner position is marked by a red circle

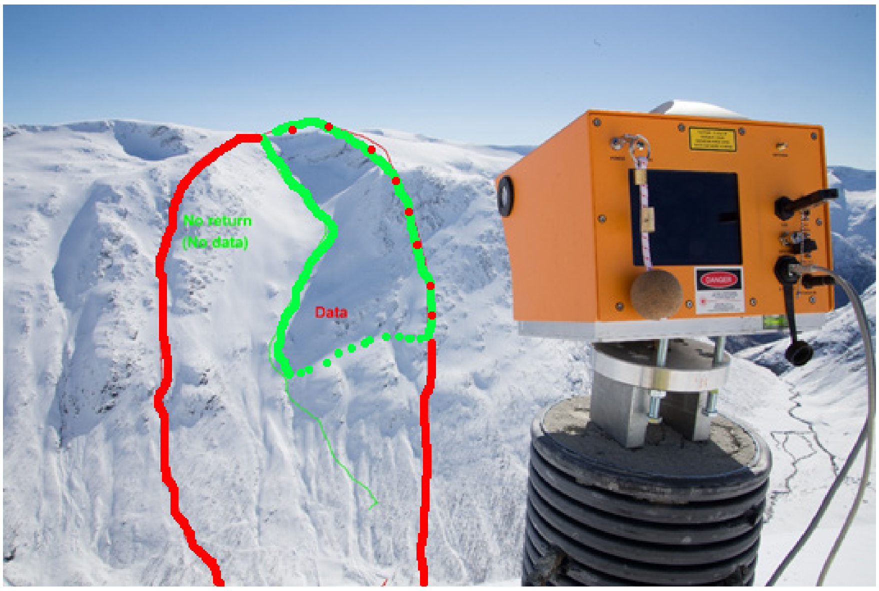

Figure 4 The laser scanner mounted on the concrete pillar at the summit of Sætreskarsfjellet, with the upper reach of the Ryggfonn path in the background

The test scans in 2011 were performed under sunny conditions, but with most of the scan area in the shadow. In those tests, the small parts of the scanned area that were exposed to direct sunlight nevertheless produced good data. It is yet unclear whether this was due to the smallness of the sun-exposed area or to better performance of the tested Optech Ilris scanner compared to the one purchased in 2012.

Neither of the scans performed with NGI's scanner at Ryggfonn in 2015 and 2018 produced usable data in areas exposed to direct sunlight. This problem with the direct sunlight was verified by test scans conducted at Venabygdsfjellet in 2017 under cloudy conditions and at Finse in 2018 under sunny conditions. The scans from Venabygdsfjellet produced good data while the scanner performed very poorly at Finse, especially before sunset.

2.2.3 Data analysis

Scaling behavior of maximum front velocity of major avalanches

During 2017/2018, the comparison of data from Ryggfonn with measurements and observations from other sites was continued, resulting in two publications (Gauer, 2018a; McClung and Gauer, 2018). A scaling analysis using a simple mass block model, supported by observations and measurements of snow avalanches, indicates that the maximum front velocity of major avalanches scales with the total drop height as $U_{\max} \sim \sqrt{gH_{\mathrm{sc}}/2}$ and that the mean velocity is $\overline{U} \approx \frac{2}{\pi} U_{\max} \approx 0.64\, U_{\max}$; here, H_{sc} is the maximum drop height, i.e., for major avalanches usually the altitude difference from the release area to the valley bottom. The analyses also suggest that the effective friction depends on the mean slope angle. This has important implications for the choice of the rheological model in avalanche simulations, as already mentioned in last year's annual report.

Furthermore, the observations may also help to estimate run-out probabilities. Figure 5 shows exceedance probabilities (i.e. the probability to observe a value larger than a given one) for a series of observed $U_{\max}/\sqrt{gH_{\mathrm{sc}}/2}$ (McClung and Gauer, 2018) and expected α values according to the α-β model (Lied and Bakkehøi, 1980). The CCDF of $U_{\max}$ shows surprisingly little scatter and is very well approximated by a Generalized Extreme Value distribution.

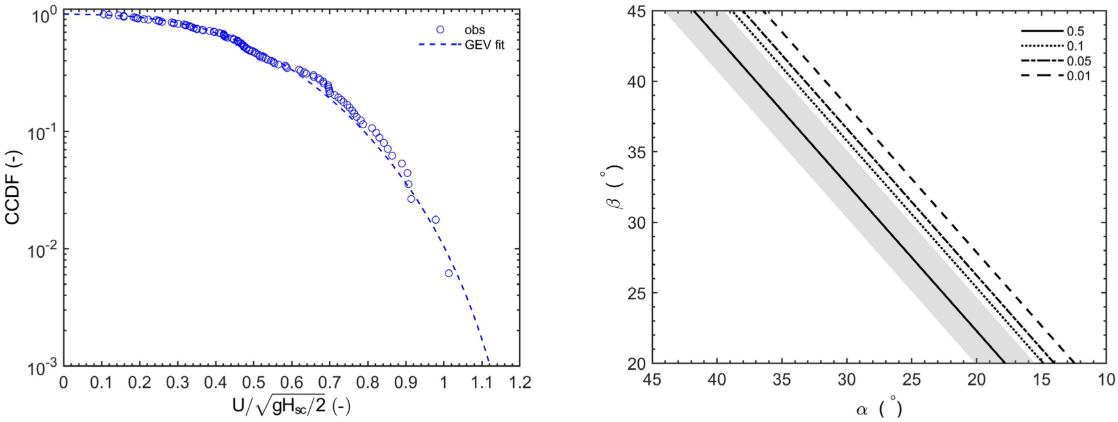

Figure 5 Complementary Cumulative Distribution Function (CCDF, survivor function) of observed values of $U_{max}/\sqrt{gH_{sc}/2}$ (left panel) and estimated exceedance probability of α versus β according to the α-β model (Lied and Bakkehøi, 1980) for major avalanche events (right panel).

The CCDF of $U_{\max}$ and the statistical relation between α and β can be combined into a CCDF for $\alpha(\beta)$ if one chooses a suitable dynamical model and some specific path profile shape. The scaling relation $U_{\max} \propto \sqrt{H_{sc}}$ strongly suggests an effective friction law close to a Coulomb relation, but with a friction coefficient that depends on the mean slope angle β. Figure 6 shows the calculated (dimensionless) velocity of a mass block moving with a constant retarding acceleration along a cycloidal track. The retarding acceleration is chosen in such a way that the mass block stops at, respectively, the β-point (which is close to the $\alpha_m+1\sigma$ -point), the α_m-point, or at the $\alpha_m-1\sigma$ -point. In these cases, the corresponding dimensionless maximum velocity $U_{\max}/\sqrt{gH_{sc}/2}$ is 0.76, 0.86 and 0.96, respectively. According to Figure 5, such maximum velocities are attained or exceeded by, respectively, 12%, 6% and less than 2% of all avalanches occurring in the path. Comparing these results with the observations in Figure 5 suggests that the simulated runouts as well as the velocities agree with the assumption that the velocity curves in Figure 6 reflect major dry avalanches. If one observes or estimates (see Sec. 6.3) that avalanches of any size in some path occur, say, once in 6 years, the α_m-point is reached about once in 100 years on average.

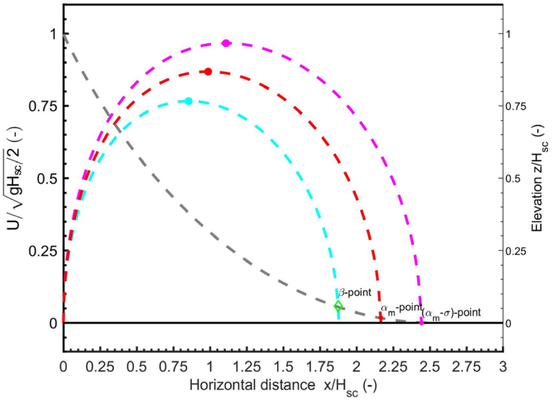

Figure 6 Velocity of a mass block moving with a constant retarding acceleration along a cycloidal track (gray dashed line; steepness in release area is ϕ_0 = 40°) and reaching (1) the β-point (cyan dashed line), (2) the α_m-point (red dashed line), and 3) the $\alpha_m-1\sigma$-point (magenta dashed line). The corresponding maximum velocities are marked with a dot •.

Estimates of the reach of the powder part of avalanches

The destructive effect of the suspension cloud or air blast of avalanches can often be observed a considerable distance ahead of the more obvious deposits of the dense part of those avalanches. Avalanche observations from Norway, Austria and Switzerland (Figure 7, right panel), which distinguish between the dense (fluidized) flow and the powder part, are analyzed to obtain probability information about the reach of the powder part (Gauer, 2018b). The analysis suggests that the relative run-out distance between the powder part and the dense (fluidized) part increases with increasing mean slope angle of the track. The data provide useful hints for avalanche practitioners about the reach and the corresponding probabilities of the powder part of avalanches (Figure 8).

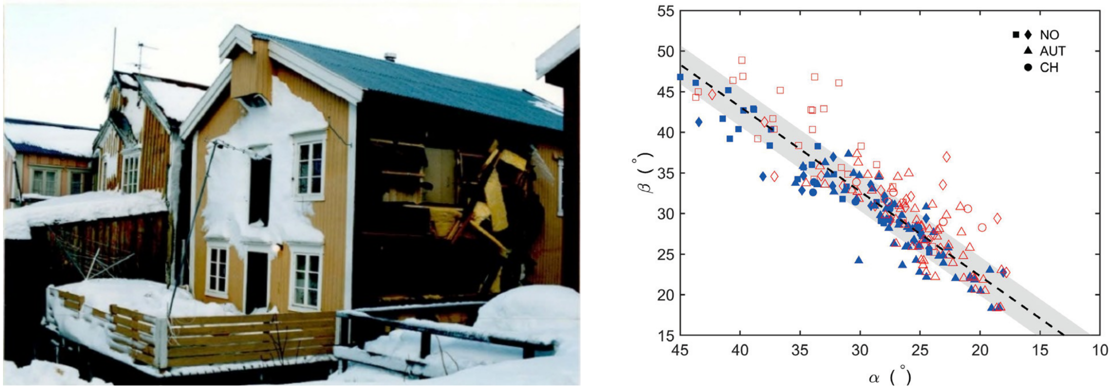

Figure 7 Signs of "air blast" impacts: right) snow deposits and damage caused by the 'skredvind' of the powder snow avalanche from Stortuva, Mosjøen, Norway, on 29.02.1996 (photo NGI); left). α-angle of the dense part (filled marker) and for the reach of powder part of the avalanches (open marker) versus the β-angle. The dashed line shows the fit angle $\bar{\alpha}(\beta) = 0.96\beta - 1.4°$ according to (Lied and Bakkehøi, 1980) and the gray-shaded area marks the corresponding $\pm 1\sigma$-range

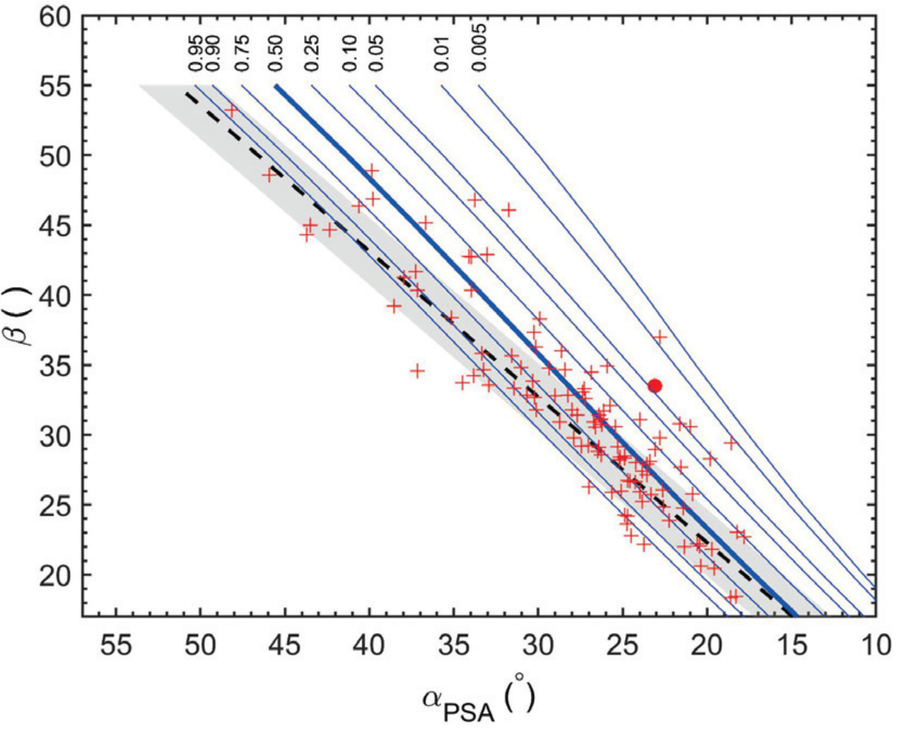

Figure 8 Estimated survival probability of α_{PSA} versus β (full black lines). The crosses show the observations (for more details see Gauer, 2018b). For comparison, the dashed line shows the α-β relation $\bar{\alpha}(\beta) = 0.96\beta - 1.4°$ and the gray-shaded area marks the corresponding ±1σ-range.

2.3 Model development

This section constitutes Deliverable D1.4.

The original budget for this activity was modest and was mainly intended for covering small improvements to MoT-Voellmy (see Sec. 2.3.1). Shortage of manpower in WPs 3 and 5 offered the opportunity to start a systematic validation of MoT-Voellmy through supervision of a MSc thesis, to extend various modules of the new program package NAKSIN (Nye AktsomhetsKart Snøskred I Norge) and to make them more streamlined and user-friendly by embedding them in a Geographical Information System (GIS), as described in Sec. 2.3.2. Finally, Sec. 2.3.3 summarizes a concept study for an efficient tool for probabilistic run-out analysis in complex terrain based on MoT-Voellmy.

2.3.1 MoT-Voellmy

MoT-Voellmy is a quasi-3D dynamical run-out model developed at NGI a few years ago. It is similar to RAMMS::AVALANCHE from SLF, which is widely used in hazard mapping work also in Norway. Some of its features are a dynamically consistent entrainment module and the possibility to include the braking effect of forest stands, with both a velocity-independent component and a contribution proportional to the square of the velocity.

Theoretical considerations combined with results from laboratory experiments on granular flow past cylindrical obstacles led to an improved formulation of the braking effect of forest stands. This new formula has been implemented in MoT-Voellmy in 2018.

As part of her MSc thesis, Marte F. Busengdal (Dept. of Geosciences, UiO) is thoroughly testing the MoT-Voellmy, which was developed at NGI some years ago. The thesis is to be delivered in June 2019. SP 4 FoU Snøskred contributes to this thesis through the financing of her scientific supervision (by D. Issler).

The validation comprises the following steps:

- a systematic study of the grid-size dependence of run-out distance, deposit depth and maximum velocity in simple topographies,
- comparison of terminal velocity and acceleration on an inclined plane between MoT-Voellmy and analytical solutions,
- a systematic study of the effect of entrainment on the dynamics of the avalanche, and
- comparison between RAMMS::AVALANCHE and MoT-Voellmy in selected case studies.

This work will constitute an official validation report for this model. If possible, the study will give recommendations on how to modify the standard calibration for RAMMS, which is also often used for MoT-Voellmy, when the entrainment module in MoT-Voellmy is used.

Two of the selected case studies are the well-documented avalanche events 2008 in the Makunosawa Valley in Japan and 2017 in Rigopiano, central Italy. Both avalanches flowed in complex terrain and damaged extensive mature forest stands. The former is highly interesting because one half of the avalanche flowed into a dense cedar stand and was stopped more rapidly than the other part in open terrain. Takeuchi et al. (2019) used the quasi-3D dynamical model Titan2D to simulate the Makunosawa avalanche and reported that the parameters could not be tuned in such a way that the simulated avalanche reached the destroyed cedar stand yet stopped at the observed distance in the open field.

2.3.2 GIS tools

In a separate project, NGI has been developing the program package NAKSIN (**N**ye **A**ktsomhets**K**art for **S**nøskred **I** **N**orge) for semi-automatically generating avalanche hazard indication maps for areas ranging from a few to a few hundred square kilometers. The key innovations relative to the present, second-generation maps are (i) use of a quasi-3D dynamical run-out model (MoT-Voellmy) instead of a topographical-statistical model (α-β model), (ii) use of refined criteria for finding potential release areas (PRAs), (iii) probabilistic calculation of avalanche release probabilities for each PRA based on local climate data, and (iv) inclusion of the effect of forest stands on release probability and run-out distance.

One of the design requirements for NAKSIN was that it should be based on open standards and not be tied to any specific operating system or GIS. Except for the run-out model, the program consists of Python scripts. This makes it possible to embed NAKSIN in any GIS that offers a Python programming interface. Such embedding may be desirable to facilitate preparation of cartographic input data and production of the final, suitably symbolized hazard indication map.

It soon became clear that the different modules of NAKSIN can be adapted for use in generating detailed hazard maps and have the potential for streamlining this process significantly. It was therefore decided to make stand-alone ArcGIS Pro tools from three of the key NAKSIN modules:

Potential release areas

In detailed hazard mapping, release areas to be simulated with a dynamical model have been delineated manually by the avalanche experts. In this way, they can account for specific terrain features, the dominant wind direction, the local climatic conditions and available observations. However, this approach is time-consuming in extended areas or in complex terrain, and it is rather subjective. In contrast, NAKSIN separates the process into two stages—first, PRAs are identified using specific and purely topographic criteria (to be described below), and afterwards the release probability is estimated for each identified PRA (see paragraph Release probabilities below).

In its present development stage, the PRA module applies the following criteria:

1. Slope angle between a lower and upper, user-selected limit (typically 26–30° and 55–60°, respectively).
2. Exclusion of sharp terrain shoulders whose planform curvature is less than a user-selected negative value (typically 0.05/m); this may divide patches.
3. Iterative elimination of isolated “outstickers” and “bottlenecks”. Outstickers are defined as cells three or four of whose edges are part of the patch boundary. Bottlenecks are characterized by two opposite cell edges being part of the patch boundary (the latter criterion may divide patches into two).
4. Inclusion of small non-release “islands” within a PRA patch.
5. Elimination of patches whose area falls below a user-selected threshold (typically about 300–500 m^2).
6. Numbering of all isolated patches.
7. Patches with a vertical extent above a user-specified threshold (typically 400 m) are “eroded” from below until the vertical extent falls below the threshold.
8. Patches larger than a user-defined upper limit are divided up using a watershed algorithm.
9. Criteria 3–6 are applied again until no further changes occur.

This new module has also been integrated into StatPack; see Figure 11 for an example.

Spatially variable friction parameters

Voellmy-type dynamical models like RAMMS::AVALANCHE and MoT-Voellmy do not adequately describe the complex processes of avalanche flow. Consequently, the model shortcomings must be compensated (approximately) by carefully tuning the friction parameters μ and k (or $\xi = g/k$ for RAMMS) to the problem. SLF (2017) contains a table of recommended friction parameters for RAMMS according to four different return periods (10, 30, 100, 300 y), three different altitude zones (below 1000 m a.s.l., from 1000 to 1500 m a.s.l, above 1500 m a.s.l.), four different terrain types (open slope, non-channelized, channelized, gully), and four avalanche volume categories (tiny – less than 5,000 m^3; small – 5,000–25,000 m^3; medium – 25,000–60,000 m^3; large – more than 60,000 m^3). When run in the graphical user interface, RAMMS uses locally varying friction parameters that are interpolated from the initial data (target return period and release volume) and the terrain model (altitude and planform curvature) in some undisclosed way.

NGI's extensive tests and applications of RAMMS to Norwegian avalanche paths have shown that plausible run-out distances result if SLF's calibration is applied with adjustments of the altitude zones—for example, the alpine zone will start already at 500–1000 m a.s.l. in Norway rather than at 1500 m a.s.l.

Based on this and the close similarity between RAMMS::AVALANCHE and MoT-Voellmy, NAKSIN adopts and interpolates the published table of friction parameters for a return period of 300 y. However, instead of using altitude as a proxy for (snow) temperature, NAKSIN works directly with the local mean winter temperature, T_w, which is interpolated as $T_w(Z) = T_{w,0} + \Lambda Z$ for a computational cell at altitude Z. $T_{w,0}$ is the mean winter temperature at sea level, Λ the lapse rate. In Norway, these parameters can be estimated from the climate maps published on-line by SeNorge.no. From climate data from Switzerland, published on-line by MeteoSchweiz, a satisfactory correlation of T_w with Z is found (Figure 9). According to this, the boundary between the low-land and sub-alpine zones is about −1.8°C, that between the sub-alpine and alpine zones approximately −3.8°C.

As an added feature compared to the NAKSIN module, the new stand-alone ArcGIS Pro tool allows the user to select a target return period between 1 y and 5000 y. For values between 10 y and 300 y, logarithmic interpolation between the two neighboring tabulated friction values is used; for return periods between 1 y and 10 y or between 300 y and 5000 y, logarithmic extrapolation from the values for 10 y and 30 y or 100 y and 300 y is applied, respectively. Note that this extrapolation is to be considered experimental until it has been extensively tested at avalanche paths either with a long series of records or with events with confirmed extremely long return periods.

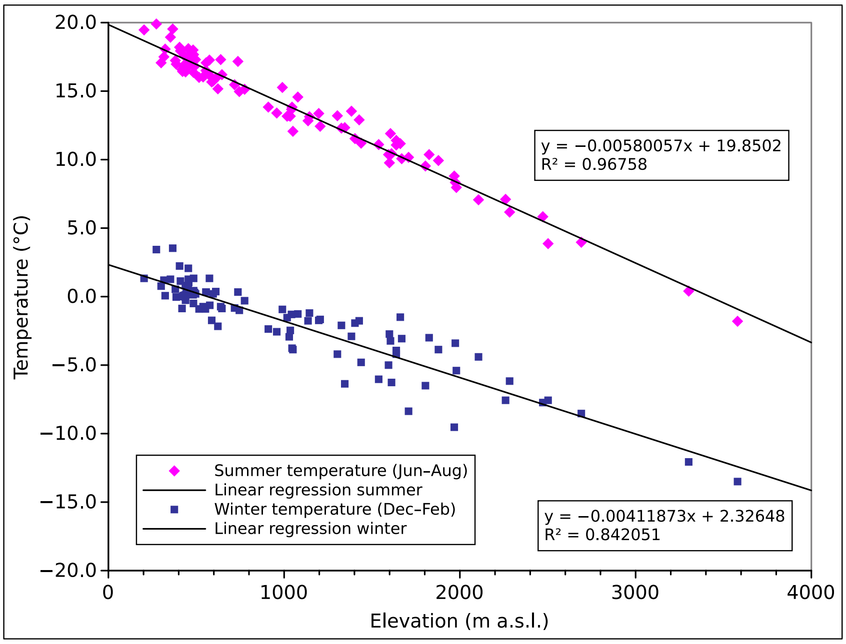

Figure 9 Correlation between mean winter/summer temperature and altitude for Switzerland, based on normal-temperature data 1961–1990 from MeteoSchweiz

Release probabilities

Work on this tool has been initiated in 2018, but it will be completed only in early 2019.

In hazard mapping, the release probability associated with a given release area is usually assessed by the expert either as "negligible" or "relevant", according to available observations or subjective criteria where there is no positive evidence of past events. Only very few systems for estimating these probabilities have been developed so far (Buisson and Charlier, 1993; Chernouss and Fedorenko, 2001). However, a realistic and objective

method for avalanche hazard mapping urgently requires a procedure for estimating release probability as a function of terrain properties and climatic conditions.
As described in Sec. 3.1, StatPack achieves this goal by using a set of fuzzy rules embodying the qualitative or semi-quantitative opinions of experts. In contrast, NAKSIN uses a simplified mechanical stability criterion (infinite-slope stability criterion) and calculates the (cumulative) PDF of the factor-of-safety through a Monte Carlo simulation, in which the old-snow depth, the new-snow depth, the location of the weak layer and its shear strength are treated as random variables according to pre-defined (cumulative) PDFs. An important strength of NAKSIN's approach is the possibility to include the stabilizing effect of a forest stand explicitly and quantitatively.

In the new tool, the user selects the PRAs to be evaluated and specifies

- the digital terrain model,
- two coefficients $T_{w,0}$ (mean winter temperature at sea level) and Λ (lapse rate for winter temperature),
- the cumulative PDF for old-snow depth and 3-days snow fall,
- a target avalanche frequency,
- and the number of Monte Carlo trials to execute.

The ArcGIS Pro tool then calculates the annual release probability as the mean number of snowfall episodes per year multiplied by the ratio of “successful” trials (i.e., leading to avalanche release) and total number of trials. If this probability is larger than the target avalanche frequency, the expected fracture height of avalanches with frequency equal to the target release frequency can also be extracted.

2.3.3 Probabilistic run-out analysis

Simulations of avalanches with dynamical models are fraught with significant uncertainties. First, there is the epistemic uncertainty that the model does not adequately capture the complex dynamics of snow avalanches. It is well known that the bed friction in the still popular Voellmy model increases much more rapidly with velocity than what experiments on granular flows and measurements of full-size avalanches indicate. Moreover, it does not distinguish between different flow regimes, nor do many implementations consider snow entrainment during the flow. However, even with a perfect flow model there would be uncertainties related to the model parameters because the latter would depend on the snow properties, which themselves depend on the weather conditions at and before the time of the avalanche descent. The same holds for the initial and boundary conditions (fracture depth, properties of the erodible snow along the path).

This suggests that one should not consider avalanche flow as a strictly deterministic phenomenon, but that the model parameters, initial and boundary conditions should be treated as random variables with their respective probability distribution functions (PDFs). Then simulated quantities like the run-out distance and maximum speed also become random variables. Their PDFs can be approximately determined by, e.g., the Monte Carlo, FORM (first-order reliability method) or SORM (second-order reliability method) techniques. From such calculations, one may extract both estimates of the uncertainty of the calculated run-out distance for a given return period or of the dependence of the run-out distance on the return period.

The probabilistic approach to hazard mapping was pioneered at least 20 years ago (e.g., Barbolini, 1999; Chernouss and Fedorenko, 2001), but has not been widely adopted yet. There seem to be two main reasons for this: First, a probabilistic approach will often be implemented as a Monte Carlo process that typically requires 10^3 or more simulations with the dynamical model. Second, natural hazards-related legislation and administrative procedures in most countries are not able to handle uncertainty: Hazard zoning with respect to, e.g., limits on frequency and/or pressure requires sharp boundaries between different categories of degree of hazard. However, the increasing power of modern computers—particularly regarding parallel processing—is about to invalidate the first objection. Due to the growing focus on risk analysis as a basis for political and administrative decisions, uncertainty considerations have finally entered the arena. For this reason, it was considered timely to develop a tool for probabilistic run-out analysis for snow avalanches now.

In the first design stage, it was decided to use MoT-Voellmy (see Sec. 2.3.1) as the simulation engine because NGI owns the source code and the code is fast. The NGI Technical Note 20170131-10-TN (Issler and Liu, 2018) explains and rates three different options for embedding MoT-Voellmy in a Monte Carlo simulator:

A. a simple Python script drawing random values for the friction parameters and fracture depth, preparing the corresponding input files for MoT-Voellmy and running it in concurrent processes;
B. a hybrid method where MoT-Voellmy is modified to receive variables and arrays from a Python script that prepares them according to the chosen PDFs and passes them to concurrent processes;
C. an extension to the ISO-C code of MoT-Voellmy where the main routine draws the random parameter values and passes all relevant variables and arrays as arguments to the computational core in concurrent processes.

The Technical Note concludes that method A requires the least programming effort but is plagued by a large computational overhead because a great amount of data is passed as ASCII files between the script and MoT-Voellmy. Method B promises a substantial speed-up at the expense of more complex programming work on two different codes. The most efficient variant is C, yet the development effort is expected to be less than in method B.

Based on these considerations, variant C was selected, and programming will start in early 2019 as part of an internal R&D project.

3 WP 2 – Statistical tools

The program package StatPack calculates the spatial distribution of the probability of a given point to be hit by a snow avalanche within the next 24 hours based on the weather conditions and the terrain. The primary focus in WP 2 this year was to improve StatPack further. This includes intensively testing of the calculated probability of avalanche triggering probability (ATP), as well as improvement of the calculations of the probabilities of being hit (runout) by clustering individual triggered cells into release areas.

3.1 Triggering probability

As described in the annual report of 2017, the model contains two main parts: 1) the calculation of the probability of a computational cell to be triggered and 2) the probability distribution along the slide path (runout). The probability of a point being hit by a snow avalanche is then found by multiplying the conditional probability of a triggered avalanche to reach that point with the probability of an avalanche to be released.

The rules used for calculating the ATP are based on expert judgments. To assure that the Fuzzy system calculates reasonable ATPs, thorough sensitivity tests have been performed. In addition, two experts independently prepared their separate sets of rules during the model development process. Three-dimensional projections were printed out for each of these sets (not shown here), and the Fuzzy inference outputs from both sets were compared to estimate the influence of possible differences in the experts' judgement. Finally, both experts agreed on a hybrid set of rules that comprises their combined beliefs. The hybrid set of rules was similarly evaluated by visual inspection of the three-dimensional projections of the hybrid Fuzzy set, see the example in Figure 10, and through a sensitivity analysis. Afterwards, it was tested against two real data sets (described in the report in preparation). Both tests showed very good results, which are summarized in an article in preparation. The hybrid set of rules is now considered final.

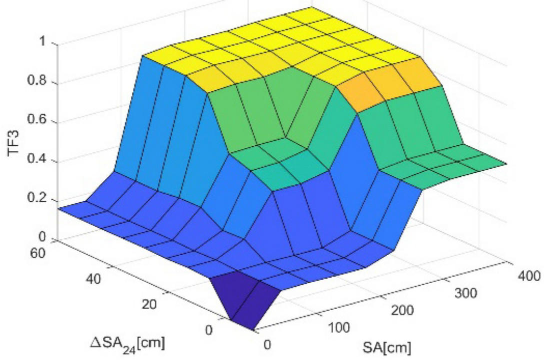

Figure 10: Example of a three-dimensional projection of the effect of the snow depth (SA) and the change in snow depth (ΔSA_{24}) on the triggering factor.

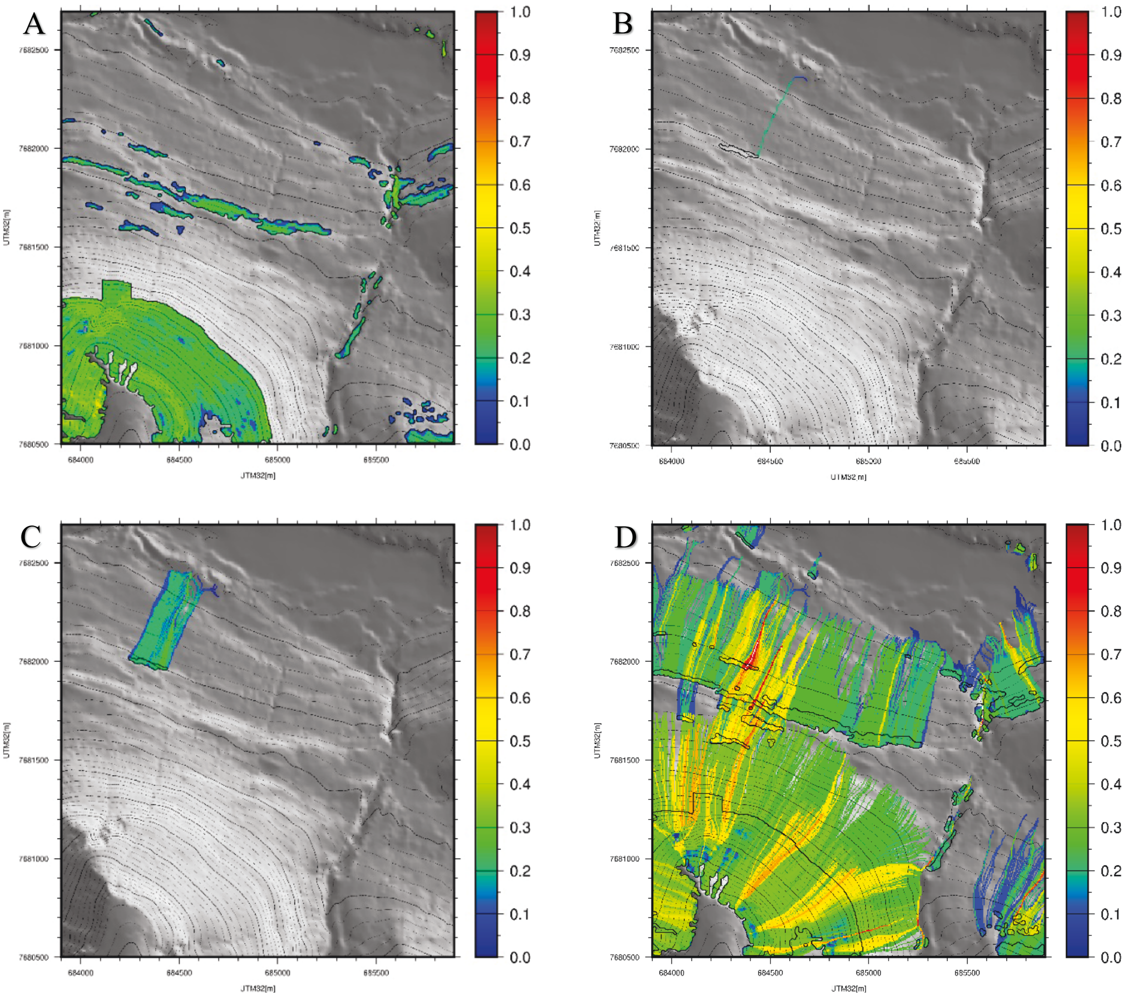

Figure 11: A - The probability of release for whole area. The computation of the probability of being hit from a single "avalanche" from one triggering cell (B) and from all cells (C) in a release area. The final hazard map (probability of hit) based on avalanches from all potential release areas.

3.2 Slide path

From each cell that is triggered, a slide path must be calculated. The procedure for calculating this path has been improved. The earlier method propagated the “avalanche” from one cell to the neighboring cell that has the lowest altitude among the eight neighbors. This can lead to abrupt and unphysical direction changes in gullies or to avalanches propagating obliquely to the isolines in open slopes that are not oriented along the coordinate directions or the diagonals. This procedure was found to produce artefacts in the run-out zone (sparse “fingers”) in many cases.

In the new version, the slide path is chosen as the line of steepest descent, see panel B in Figure 11. All cells that are closest to this path are marked as hit. This algorithm ensures that the avalanches follow the terrain and do not drift obliquely across open slopes, where they might accidentally end up in the wrong gully. Note, however, that such flow routing—which is an excellent approximation for the run-off of surface water—will not correctly capture the motion of fast avalanches in sharp bends, where they may break out of the gully. Neither does it consider that avalanches release as slabs where earth pressure counteracts the tendency of the flow to move towards the centerline of the gully. Nevertheless, the new algorithm produces much more realistic run-out areas (Figure 11 C and D).

3.3 Release areas

The definition of release areas was also substantially improved. In the previous version of StatPack, each cell with a slope angle between 28° and 70° was treated as a separate "avalanche release area". In reality, avalanches release as extended slabs comprising many cells of the terrain model. The new version of StatPack adapts the algorithms for finding potential release areas (PRAs) that were developed at NGI for the program package NAKSIN (**N**ye **A**ktsomhets**K**art **S**nøskred **I** **N**orge), which semi-automatically calculates avalanche hazard indication maps (Issler et al., in prep.; NGI, 2018b). Cells are coupled in potential release areas. Potential release areas are determined based on topographic criteria (Figure 12):

- The slope angle must be in a certain range (e.g. between 28° and 70°).
- The planform curvature must not be below some threshold, i.e., the fracture will not propagate across sharp shoulders, which usually are bare of snow due to the wind.
- "Outstickers" and "bottlenecks" are removed in an iterative procedure.
- Small islands that do not fulfil the release criteria but are completely surrounded by release cells are also included in the release area.
- Parts of a PRA that are farther below its topmost point than some limit (typically 400 m) are removed.
- Very large PRAs are divided into several smaller PRAs according to their drainage basins. After this procedure, the new PRAs are subjected to some of the previous steps again.

In the present version of StatPack, the release probability is calculated independently for each cell in each PRA and used in the calculation of hit probability along the line of steepest descent originating from that cell, as described in Sec. 3.2. In earlier versions of StatPack, the hit probability in any given cell was calculated as the sum of the hit probabilities from all possible flowlines. The new version proceeds as follows:

- For each PRA, the *maximum* of the hit probabilities of flowlines originating in this PRA is determined (exemplified in panel C of Figure 11).
- If flowlines from several distinct PRAs touch a cell, its total hit probability is the *sum* of the hit probabilities over all PRAs concerned (Figure 11, panel D).

This algorithm ensures that the *conditional* probability of a cell being hit if an avalanche releases from a single PRA is at most 1. On the other hand, the possibility of multiple hits from different PRAs is properly accounted for.

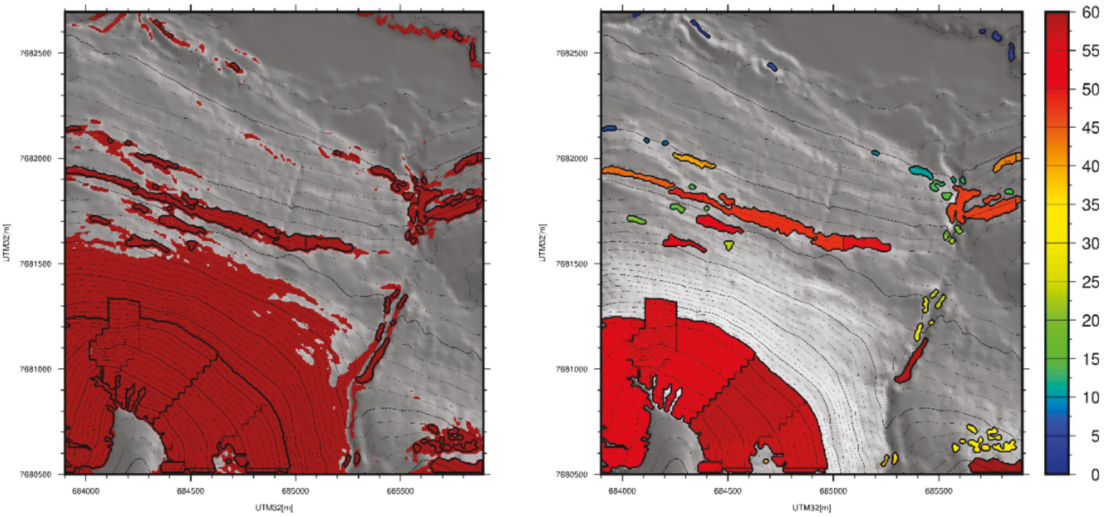

Figure 12: Areas with slope angle between 28° and 70° (left) and the release areas determined by StatPack (right). The 60 release areas in total are numbered and color-coded according to their number (see color bar on the right). Note that the largest connected patch in the left panel has been split into separate release areas and that its total area was significantly reduced by the requirement that release areas not extend over more than 400 m in altitude

3.4 Further work and potential improvements

In 2019, the following work is planned:

- The probability distribution function of run-out along a flowpath is too much concentrated around the mean α angle and needs to be adjusted.
- Intensive testing against documented snow avalanches. This will be the topic of the MSc thesis of Ole Bjørn Kanstad (Dept. of Geosciences, UiO) in 2019: SP 4 FoU Snøskred will provide supervision for the student's work.
- Furthermore, options for estimating and including the probability of different weather conditions to occur will be studied.

3.5 Impact of mitigation measures on land-use planning

Due to manpower shortage in 2018, the start of work on this task was deferred to early 2019. In the meantime, contacts with the municipalities of Stryn (Sogn and Fjordane County) and Ørsta (Møre og Romsdal County) opened new perspectives for the planned investigation: On the one hand, the Law on Planning and Construction (Plan- og bygningsloven) sets very strict standards for avalanche safety in construction areas, but it opens for the possibility of using mildly endangered areas if the buildings are dimensioned to withstand the load from avalanches. On the other hand, novel construction techniques and materials, like cross-laminated timber (CLT), allow constructing resilient buildings with a low CO_2 footprint at much lower prices than if reinforced concrete were used.

When these two innovations are combined, new perspectives arise in areas of Norway where natural hazards—particularly snow avalanches—severely limit the possibilities for economic development and population growth or stabilization. In this context, the following questions arise and ought to be studied to provide a factual basis for future political decisions:

- How much area can be reclaimed for construction in this way, and how can the socio-economic impact of these new opportunities be described and quantified?
- What is the extra construction cost required for appropriately dimensioning buildings?
- How can the eco-balance of widespread use of CLT building techniques be quantified?
- By how much does the combined societal risk increase (due to greatly increased exposure to the residual risk) if endangered areas are used in this way?

In the beginning of 2019, this research idea will be developed further and suitable partners with high competence in socio-economic analyses and risk quantification sought. With prof. R. Tomasi (NMBU, Ås) and the municipality of Ørsta, an expert in novel timber construction techniques and a highly interested stakeholder are already involved. NGI can contribute to this study through quantification of the avalanche pressure distribution throughout the endangered area. In the beginning of 2019, a pilot project to construct a new school building in Sæbø in CLT will be started, with NGI providing advice on avalanche pressure levels. At the same time, NGI assists NMBU in the supervision of a Master's thesis that will provide indicative values for the dimensioning of CLT buildings against given avalanche loads and for the cost of this.

4 WP 3 – Slushflows

4.1 Snow cover simulations

Due to limited manpower, no further progress was achieved in this task in 2018.

The aim for 2019 is to set up SNOWPACK for multiparameter runs where several possible tunings are run at the same time. This will allow a better possibility to choose the best model results compared to observations.

4.2 Dynamical simulations of slushflows

Due to limited manpower in 2018, only a few exploratory simulations of a slushflow event on the western flank of Mt. Fuji, Japan could be carried out. Slushflows are a frequent phenomenon at Mt. Fuji (35°N, 3774 m a.s.l.) as it receives large amounts of snow above 2000 m a.s.l. in high winter but strong sunshine and sometimes torrential rainfalls in late winter/spring. Events often start as slushflows and turn into debris flows at lower elevations where they erode large quantities of volcanic soil.

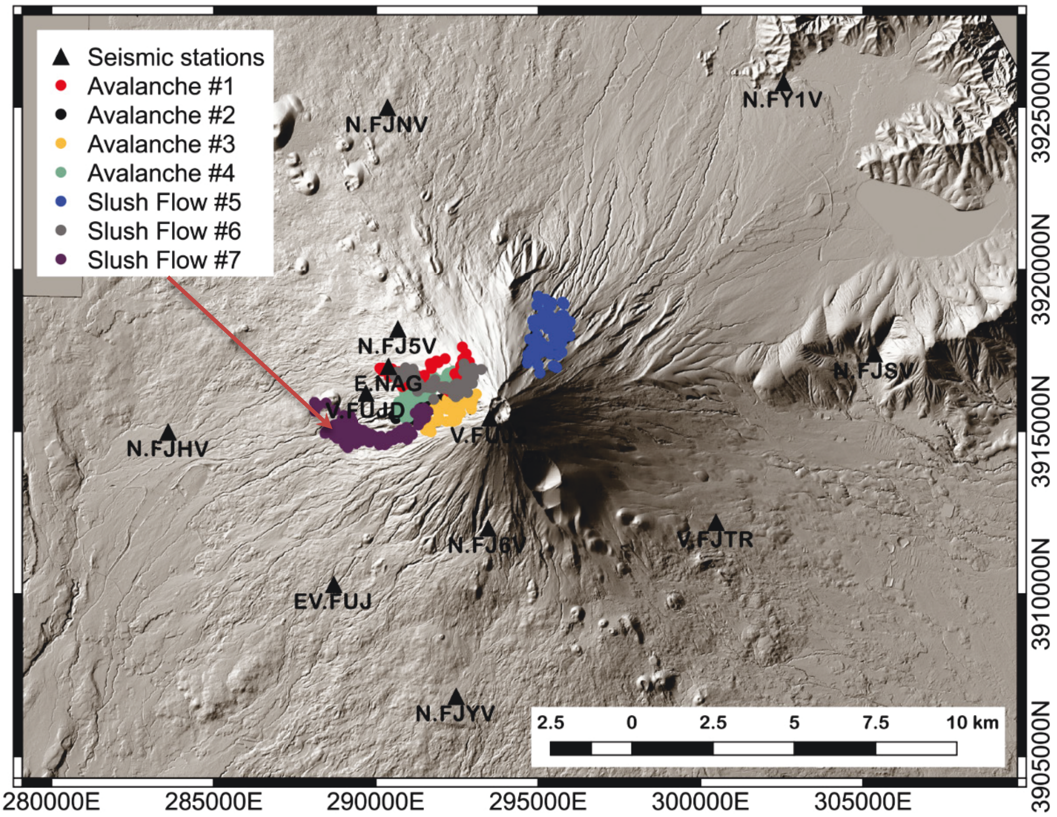

Figure 13 Map of Mt. Fuji with network of seismometers and identified avalanche and slushflow events. Event #7 was simulated with MoT-Voellmy. Map courtesy C. Pérez-Guillén

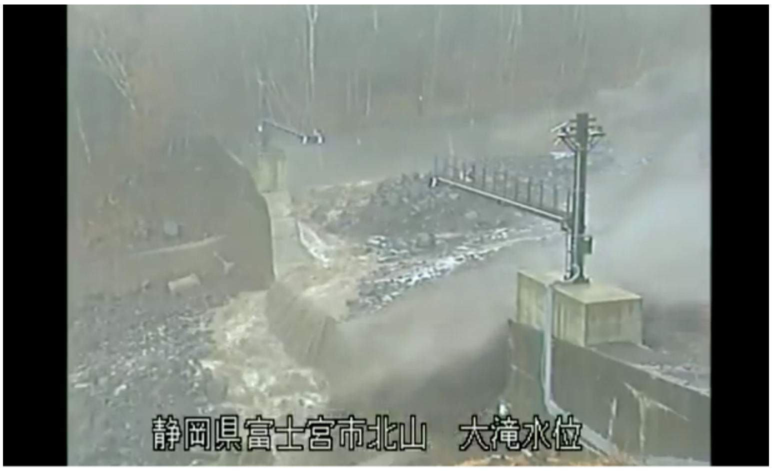

Figure 14 Still frame from video showing the slushflow of 2018-03-05 on the west flank of Mt. Fuji arriving at the gauging station at approx. 1500 m a.s.l.

In a collaboration with Nagoya University and the Mt. Fuji Research Institute of Yamanashi Prefecture, recordings of the dense seismometer network were analyzed to find and track snow avalanche and slushflow events on the flanks of Mt. Fuji in the period 2014–2018 (Pérez-Guillén et al., 2018). Numerical simulations with Titan2D and MoT-Voellmy were used to put bounds on the release volume, to assess the precision of the tracking method, and to estimate the flow velocities.

In the case of the slushflow event of 2018-03-05 (Figure 13), where a video recording at a gauging station showed the arrival of the slush-/debris flow (Figure 14), the simulated run-out and velocity were too low if the same parameters were used as in earlier applications in northern Norway and Svalbard. These discrepancies need to be investigated in more detail.

In 2019, recommendations for modeling slushflows with RAMMS or MoT Voellmy will be elaborated and disseminated. These results could also be a contribution to the standardization work (bransjestandard Faresonekartlkegging skred i bratt terreng) commissioned by NVE and to be delivered in 2019.

4.3 Circum-Arctic Slushflow Network (CASN)

The Circum-Arctic Slushflow network gathers scientists and practitioners who are working with or are interested in the phenomenon of slushflows. After the first gathering at the International Snow Science Workshop 2016 in Colorado, the network has shared their scientific library on slushflows and records of interesting slushflow events. In autumn 2017, a regional meeting for Scandinavia was organized in Oslo. In 2018, the CASN supported several students with materials and advice and worked on the proposed observation guidelines for slushflows. The plan for 2019 is to update the CASN homepage, to complete and disseminate the observation guidelines, and to issue at least four newsletters to the CASN members.

5 WP 4 – Investigation of relevant snow avalanche events

The sub-project on avalanche detection by infra-sound was continued throughout the winter 2017/2018. The objective is to test whether such a system is capable of automatically detecting snow avalanches, and one of the test areas is the Grasdalen area near NGI's research station Fonnbu in the Stryn mountains. If it performs satisfactorily, such a system could provide valuable support in avalanche forecasting and warning, both for settlements and traffic routes. This investigation is a collaboration between the National Public Road Administration (SVV), Wyssen Norway AS, and NGI.

Investigation of snow avalanches with particular properties, such as events with remarkably long run-out, particular spreading behavior or heavy damages, can provide valuable information that can be valuable input for (the development of) our modeling tools. The weather during the winter 2017/2018 was mainly characterized by a stable snow cover, and little damage from avalanches was recorded. The one exception was an avalanche near Oppdal in Trøndelag county that destroyed a cabin. NGI investigated the site and wrote a report for the attention of NVE (NGI, 2018b). Work on describing and analyzing the deadly Rigopiano avalanche in January 2017 also continued and resulted in two reports (Issler, 2018, 2019).

5.1 The infrasound project

As explained in earlier Annual Reports, an infrasound avalanche detection system was installed in Grasdalen in October 2014 by the Norwegian Public Roads Administration (NPRA) to test the feasibility of continuous avalanche monitoring. The NPRA had initially decided to discontinue the monitoring program in Grasdalen after the 2015–2016 season and to remove the infrasound detection system. Following a proposal from NGI to share the costs of operation, it was decided to continue the research program for two more seasons. During the winter 2017/2018, technical problems led to long periods of downtime. To make up for this, Wyssen Norge AS offered to leave the system operational in Grasdalen also in the winter 2018/2019 at no additional cost.

According to a preliminary summary of the experiences during the winter 2018 by SVV and Wyssen Norge AS (Minutes of meeting on 2018-10-23, by T. Humstad, NPRA), the main problems encountered in Grasdalen were the following:

- One of the sensors was mounted too close to the road, so that it was repeatedly covered with snow from the snow ploughs, which then turned into ice. During the summer 2018, the sensor was moved 10 m away from the road.
- It appears that the lid on one of the sensors was too tight, providing insufficient contact with the atmosphere.

During the winter 2018/2019, the measurements will be continued with these two problems eliminated. Whenever the system detects an avalanche, it will alert all subscribed users by SMS within two minutes after detection. The data processing routines are improved to provide better insight about the quality and reliability of automated avalanche detection. At the same time, NGI's crew providing local avalanche forecasting for this area will be able to assess the utility of this extra information.

After the end of the mountain winter season, NPRA and NGI will jointly analyze the collected data from five winters and seek answers to the following questions:

1. How reliable is this particular infrasound system?
2. Depending on avalanche size and distance, what is the probability of correct detection, of missed events and of false alarms? What recommendations can be made for operational use along exposed traffic lines?
3. To which degree can such a system support and improve local avalanche forecasting?

NGI will additionally assess the quality of (i) NGI's (manually elaborated) local avalanche forecasts and (ii) the local avalanche forecasts produced automatically by StatPack (cf. Secs. 3.1 and 3.4). All results will be made public through reports and/or publications in conference proceedings or peer-reviewed journals.

5.2 Avalanche events of special interest

Together with the report (Issler, 2018), this section represents Deliverable D4.2.

5.2.1 The avalanche disaster of Rigopiano, central Italy, on 2017-01-18

During a period of extreme snowfalls and low temperatures in the central Apennine mountains around the Gran Sasso massif in mid-January 2017, a large avalanche released on the eastern flank of Monte di Siella at approximately 1900 m a.s.l., in the municipality of Farindola, province of Pescara, Abruzzo region of central Italy. Descending about 700 m, it attained a run-out distance of more than 2 km despite plowing through a beech stand with typically 70 years old trees for about 1 km. In the run-out zone, it annihilated the four-story luxury spa hotel Rigopiano, where 40 persons were waiting for evacuation after a series of substantial earthquakes earlier that day. Of these, 29 perished in one of the deadliest snow avalanches in Europe in the past 50 years.

Due to the impending court case, a wide area around the hotel ruins was closed off during NGI's field survey in June 2017, but the release area and the track of the avalanche down to about 1300 m a.s.l. could be hiked and investigated, yielding interesting observations, particularly regarding the forest damage. It also turned out that several neighboring avalanche paths also were active at the same time. Combining observations with information collected from locals or found on the Internet, a coherent picture of avalanche activity in this southerly mountain area emerges.

In 2018, a first report on the field survey was completed (Issler, 2018) and most of a second report analyzing the observations written (Issler, 2019). In the concluding section of the first report, the question is raised whether NGI's standard methods of avalanche hazard mapping would have revealed the precarious situation of the spa hotel before the event or not. Four particularly critical steps in the analysis are the following:

Figure 15 The Hotel Rigopiano in the foreground, the densely forested Grava dei Bruciati gully in the middle ground, and Monte Siella with the avalanche release area in the background

- A thorough climate analysis should reveal that this area is subject to very intense precipitation events when (north-easterly) Bora winds, after crossing the relatively warm Adriatic Sea, rapidly ascend 2 km or more to cross the main ridge of the Apennines.
- Some local people have extensive and highly valuable knowledge of the avalanche history of the area, but it may not be straightforward for outsiders to get into contact with them. The avalanche experts cannot in all cases count on the municipal authorities to create these contacts.
- In the case of the Grava dei Bruciati path, old aerial photos clearly show that devastating avalanches have occurred in the past. Such photos were published on the Internet after the tragedy, but it might have been difficult to find these critical images under normal circumstances.
- The avalanche had to cut through 1 km of nearly mature and quite dense forest to reach the hotel. If one did not know of other avalanche events where this happened, it would be easy to consider this impossible.

The second report first estimates the mass balance of the events, inferring that most if not the entire snow cover was eroded by the avalanche, but could not be entrained into the flow completely. Then avalanche speeds at different locations along the path are estimated by treating the relevant parts of the avalanche as a mass point. From the height of a shoulder that the avalanche jumped over, the curvature of the gully bends and the superelevation of the outer trimlines, the speed of the fastest-moving, fluidized parts of the avalanche could be estimated to be in the range 30–45 m/s in the middle track, with 35–40 m/s being the most likely range. This estimate appears to be consistent with the simulations by Frigo et al. (2018), who used RAMMS and reported a speed of 30 m/s in the run-out zone at the Hotel Rigopiano. Conversely, the inner radius of the bends leads to upper bounds on the speed of the slower, dense body and tail. These velocities were apparently around 20 m/s in the middle track, i.e. about half of the speed of the avalanche head. This is very similar to earlier findings from several avalanches of different sizes (Issler et al., 2008) and consistent with measurements with range-gating Doppler radar (Gauer et al., 2007).

Rough inferences on the pressure at specific locations can be made from the utter destruction of a four-story building, its newer parts presumably constructed in reinforced concrete, and displacements of the debris by some tens of meters. More precise results could be obtained if constructional details of the building were known. Similarly estimates of the energy loss of the avalanche are highly uncertain because the necessary moment and shear for uprooting beech trees from the karstic ground with only a shallow soil layer are not well known.

Figure 16 The destroyed main wing of the Hotel Rigopiano to the left, the spa area in the middle and the original Rifugio Tito Acerbo near the forest in the background

It is planned to simulate this avalanche event with MoT-Voellmy in 2019, pending a modification of the code that will allow to account for the destruction of the forest.

5.2.2 Oppdal 2018-01-15

In the Grønlia cabin area on the east side of Skarvatnet, about 10 km NW of Oppdal, Trøndelag county, an avalanche released on January 15, 2018. It had a maximum drop height of about 130 m and a maximum run-out distance of approximately 300 m.

Figure 17 Overview of avalanche path at Grønlia, Oppdal municipality

Figure 18 One cabin was destroyed by the avalanche

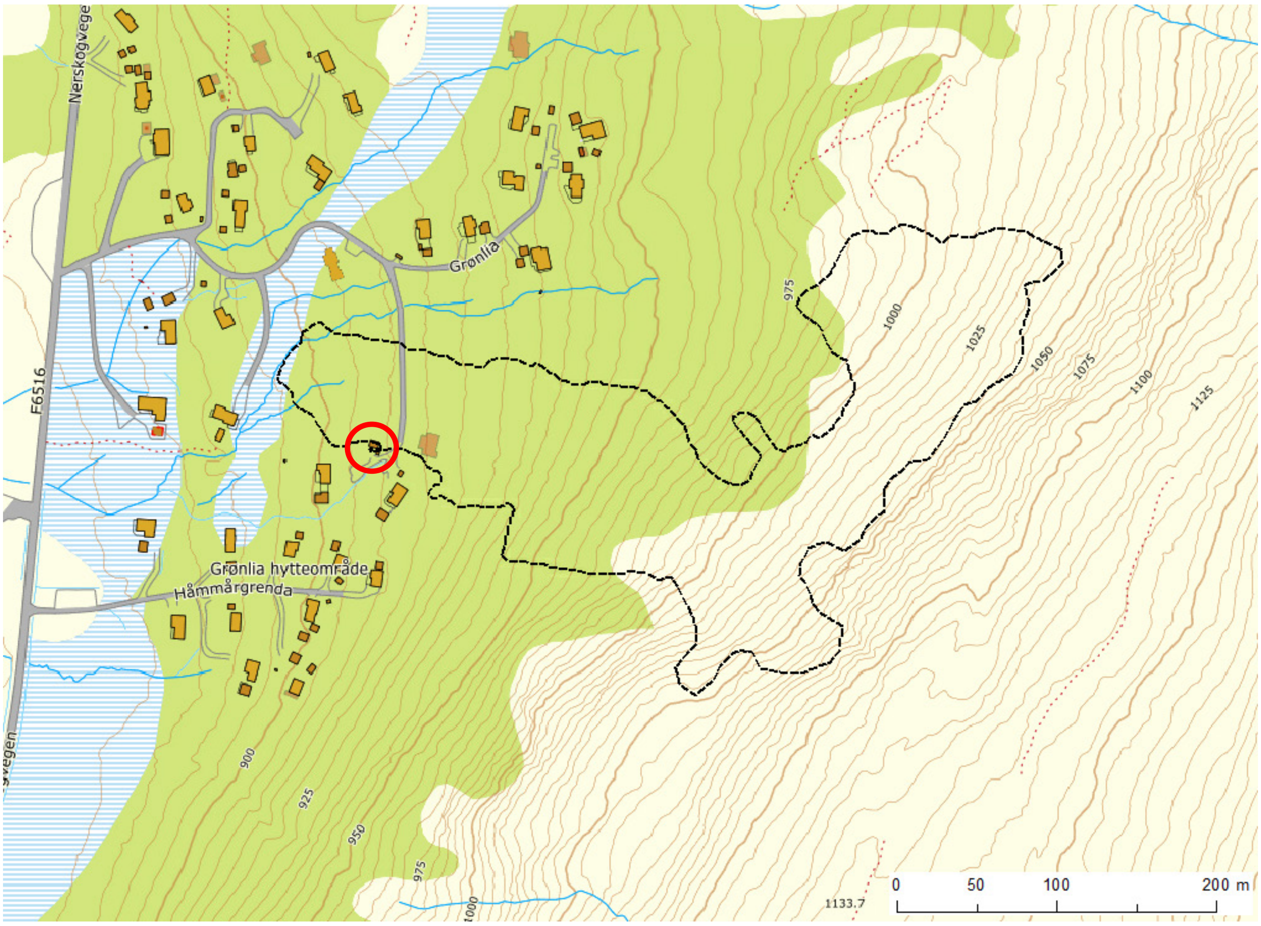

Figure 19 The dashed line indicates the perimeter of the avlanche event. The destroyed cabin is indicated by the red circle. The map indicates another cabin about 30 m upstream of the destroyed one, but it had not been constructed yet

Despite its moderate size, it destroyed one cabin that was located right at the southern edge of the avalanche perimeter, in the run-out zone (Figs. 17 and 18). NGI personnel visited the area on January 17, surveyed the avalanche perimeter and damage (Figure 19), and assessed the avalanche danger in the present situation. The results were summarized in a letter to Oppdal municipality dated January 19 (NGI, 2018a).

The avalanche released during a period without precipitation, but with strong winds and blowing snow. Before the event, the top of the snow cover consisted of large quantities of rather loose snow. These circumstances clearly reduced the stability of the snow in the slightly concave slope near the ridge and contributed to the relatively long run-out.

Subsequent back-calculations of the event with RAMMS, using the observed snow conditions as input, produced realistic results (Figure 20). Comparison with the topographical-statistical α-β model shows that the run-out distance corresponds roughly to the expected run-out distance of events with low frequency under these topographic conditions. Note, however, that the statistical basis for the α-β model is biased towards avalanches with drop heights larger than 300 m and the climatic conditions of western Norway.

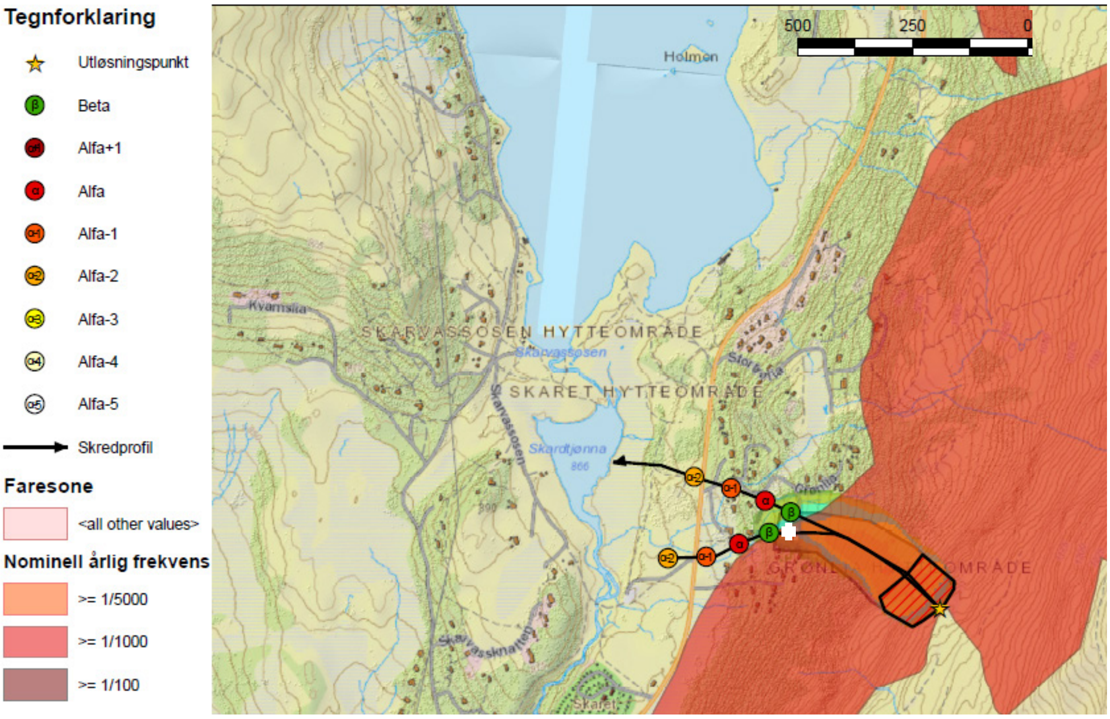

Figure 20 Simulations of the avalanche event with RAMMS. The white cross indicates the location of the cabin. The area with red hatching and black outline is the release area selected for the simulations, the perimeters of the simulated avalanches are drawn with gray, magenta and green lines for three different assumed release depths and sets of friction parameters. The colored circles on the two black, arrowed lines are the run-out predictions of the α-β model, with the β point in green and the α-point in red. The red-brown area is the area endangered by avalanches with nominal annual probability of 0.001 according to the map elaborated by NGI in 2013

6 WP 5 – Improved tools for local avalanche forecasting

6.1 Wind field in mountain topography

During 2018 several attempts were made to apply WindSim software to complex mountain terrain in Norway. Progress was hampered by both constraints in manpower for the project and continued problems with integrating the software into our systems. We will continue the efforts in 2019 and hope to achieve promising results.

6.2 Estimation of drift-snow quantity under known wind conditions

Due to the lack of results from 6.1 this task was not pursued in 2018. For 2019 we plan to couple the wind fields from 6.1 with a simple snow drift model and compare the results to available datasets of snow distribution. If possible, different drifting snow models will be tested.

6.3 Quantification of avalanche release probability

One of the main challenges regarding hazard mapping is to estimate avalanche probabilities and avalanche size for a given path. One reason for this is the lack of sufficient data. Avalanches of interest for hazard mapping (typically avalanches of relative size R4 or R5) are rare events and in addition, their detailed observations are often hindered by bad weather and hazardous conditions. Another question is how a forest cover influences the avalanche hazard. It is commonly accepted that dense forests are the most cost-effective mitigation against natural avalanche release. However, little work has been done to quantify the effect of forest cover on the release probability of avalanches. To obtain some insight on the role of these parameters, we extended a simple slab-model (Lackinger, 1989) and used a Monte-Carlo simulation approach. First, we obtained estimates of avalanche release probabilities and probability distributions of the expected fracture depth—which is an important parameter for modern numerical avalanche models—depending on climatological parameters. Then we extended the model to account for the supporting effect of forest on the snowpack. In this way, it becomes possible to quantify the efficiency of a forest and to define requirements on a forest stand as a protective forest.

Preliminary results of the model show that the obtained tendencies are consistent with observations and are in the expected range (Figs. 21 and 22).

Figure 23 illustrates how forest may influence the expected return period of avalanches. The figure depicts a comparison of simulated return periods depending on slope angle and an assumed stand density dN for climatic data from Ryggfonn.

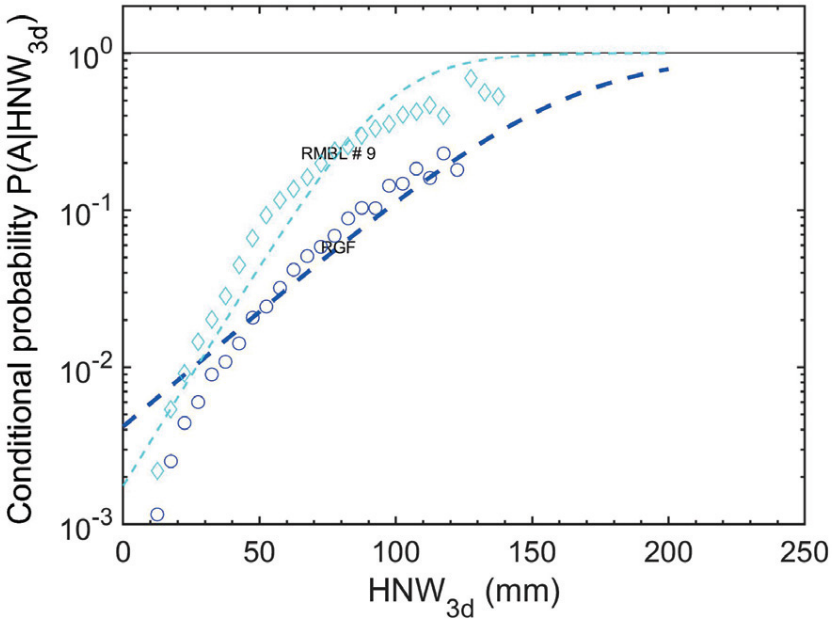

Figure 21 Distribution of the conditional probability P(A|HNW3d). Comparison of observations (lines) and simulations (dots) for data from Gothic, Colorado, USA (RMBL #9) and Ryggfonn, Norway (RGF).

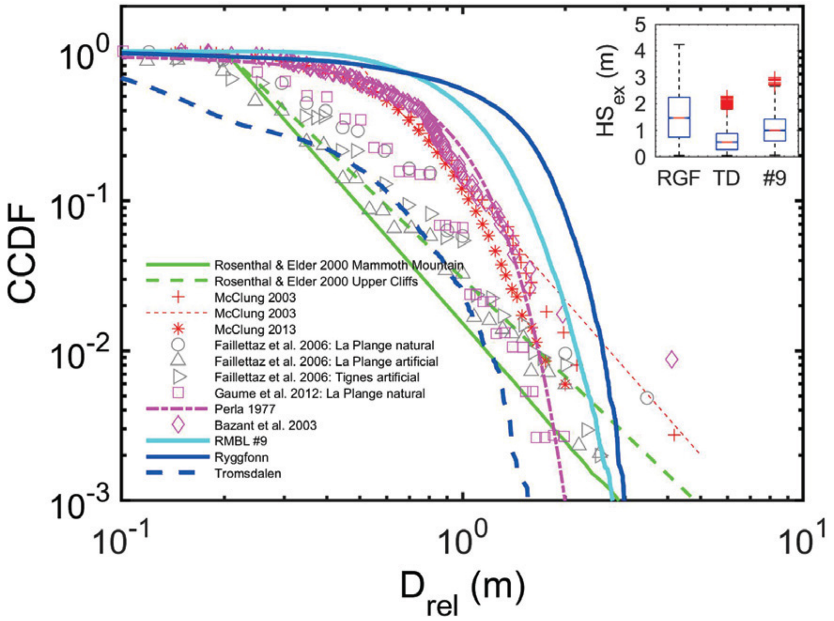

Figure 22 Complementary cumulative distribution function of fracture depth D_{rel}. Comparison between simulations for Ryggfonn (Norway), Tromsdalen (Norway), and Gothic (Colorado, USA) and observations or proposed relations in the literature. The boxplot shows the snow height distributions for the three simulations.

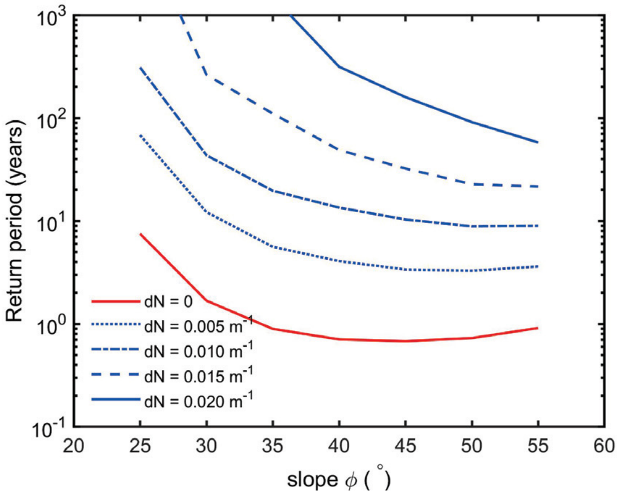

Figure 23 Comparison of the nominal return period vs mean slope angle of the release area with the stand factor d N as parameter (diameter, d, times number of trees per m^2, N).

7 Work plan and budget 2019

7.1 The need for modifications to the work plan

The workplan 2019 was not as precisely defined in the original project description as the workplans for 2017 and 2018, reflecting the difficulties to predict progress in a research project and new questions and opportunities that arise after the project proposal was drafted. Two particular circumstances lead to the need to modify the original plan somewhat: First, the changes in the workplan for 2018, which were brought about by the limited availability of key collaborators, call for extra effort in some work packages (WP 3 and WP 5) to nevertheless achieve the original goals. Second, the likely increase of the project budget 2019 from 3 to 4 MNOK calls for a careful deliberation whether these funds should be used to start a new activity or to strengthen ongoing activities that had too restricted budgets.

After weighing these alternatives, the project team strongly favors the second option:

- 2019 is the last year of the present project period. New activities that are started now can easily become a liability in the next project period, unless they can be completed in 2019. We anticipate that the work plan 2020–2022 should be developed from the ground up, without as few carry-overs from the present project period as possible.
- There is a clear need for intensified maintenance of the instrumentation at Ryggfonn, after many years of minimal renewal of aging apparatus. The priorities for renewing aging equipment can only be set after the end of the winter.
- There is a significant backlog of results from the project that have not been suitably published in peer-reviewed scientific journals due to lack of funding and work capacity.
- WPs 3 and 5 need to be funded sufficiently to achieve the original goals.
- There is increasing interest of graduate students from different Norwegian or even foreign universities for a MSc thesis topic related to SP 4 FoU Snøskred. This, in turn, calls for increased funding for advising MSc students. These students represent an outstanding opportunity to tackle interesting questions that are closely related to the main activities but could not be prioritized. In addition, in this way FoU Snøskred contributes significantly to the quality of education in the geosciences in general and natural hazards in particular. This is important for securing a sufficient number of competent natural-hazards and avalanche specialists to serve Norwegian society in the future.

7.2 Revised work plan 2019

7.2.1 WP 0 – Administration and dissemination

Besides the usual activities of project administration and reporting, two activities are particularly important throughout the last year of this project period, namely outreach and planning for the project period 2020–2022. There is nothing noteworthy about Tasks T0.1 and T0.4.

Task T0.2: The meeting of the Reference Group will be combined with a seminar presenting the main results from the project to interested avalanche experts and administrators.

Task T0.3: A list of project results that should and can be documented in high-quality publications will be set up in early 2019. How many papers can be finished in 2019 will, however, also depend on the amount of GBV funding that can be secured.

Task T0.5: Throughout the year, two to three MSc students will be working on topics within FoU Snøskred or closely related to it and will require guidance from members of the project team. Preparing and delivering the Seminar on Snow Avalanche Research in collaboration with NVE towards the end of the year will be a priority.

Task T0.6: After introductory discussions with NVE, different options for an innovative FoU Snøskred 2020–2022 will be defined and analyzed during the first half of 2019. After a further round of discussions with NVE, the prioritized elements will be assembled into the final project proposal after possible adjustments induced by feedback from the Reference Group or participants in the seminar.

7.2.2 WP 1 – Ryggfonn and avalanche dynamics

Task T1.2: Beyond the usual year-to-year maintenance, some aging critical system components will be renewed.

Task T1.3: Experience from past years indicates that the probability for more than one successful campaign at Ryggfonn are quite low. One member of the project team will participate in the small-avalanche experiments of a Japanese group in Niseko, Hokkaido with some travel support from FoU Snøskred.

Task T1.4: Depending on the success of measurement campaigns in Ryggfonn, activity in this task will be adjusted.
The report on the results of the analyses will constitute Deliverable D1.5.

Task T1.5: The following three activities—in prioritized sequence—will be carried out to the degree the available funding allows:

- Improvement of the numerical basis of MoT-Voellmy
- Equation set for a two-layer model of dry-snow avalanches
- Inclusion of progressive forest damage in the braking force due to trees in MoT-Voellmy

The results will be summarized in Deliverable D1.6.

7.2.3 WP 2 – Probabilistic methods and socio-economic aspects

Task T2.1: The remaining work with StatPack is to improve the PDF for the run-out angle, to complete the users' manual and a journal paper, and to accompany the first season of full tests in practical avalanche forecasting.

Deliverable D2.2 consists of a Users' Manual and a submitted journal article.

Task T2.2: In the beginning of 2019, it will be decided whether to proceed with the work as planned for 2018 or to replace the task with a study of the socio-economic gain and the changes of total risk that can be expected from using a rarely invoked passage of TEK17. It allows building properly reinforced houses in safety class S2 (S3) in areas that are fulfil only the requirements for safety class S1 (S2).
The results (Deliverable D2.3) will consist of a report or a Master's thesis.

7.2.4 WP 3 – Slushflows

Task T3.1: Working setup for SNOWPACK to represent Norwegian wet snow. Comparison with observations and slushflow events.

Task T3.2: Preparation of recommendations for the use of numerical models in slushflow simulations.

Task T3.3: The Circum-Arctic Slushflow Network will be active to finalize the observation guidelines, increase the international exchange and support the snow and avalanche meeting in March 2019 in Iceland.

7.2.5 WP 4 – Detection and investigation of snow-avalanche events

Task T4.1: This task will be continued as in the previous two winters, as originally planned.
The associated Deliverable D4.3 is a report on the observed avalanches and the insight gained from them.

Task T4.2: Data collection will continue during the winter 2019 at no extra cost. During the summer, data analysis will be carried out in collaboration with SVV (National Public Road Administration).
The results of the analysis will be reported as Deliverable D4.4.

7.2.6 WP 5 – Improved tools for local avalanche forecasting

Task T5.1: The work with WindSim needs to be continued so that the program can be routinely applied to simulate local wind fields in mountain terrain for different geostrophic wind situations.
The results will be reported as Deliverable D5.1.

Task T5.2: This task has been deemed too ambitious in the present project period, given the difficulties encountered in Task T5.1. The related deliverable D5.3 is canceled.

Task T5.3: The work on modeling the probability for avalanche release will be continued. StatPack already provides an approach to estimate the release probability of (relatively frequent) avalanches within the next 24 hours, based on meteorological and terrain input data and fuzzy rules. For this reason, the emphasis in this task will be on very rare events and the use of climate data. Important questions will be how mesoscale climate data can be downscaled to the size of release areas, how blowing

snow can be integrated into this analysis and how one can build a model that does not require supercomputing resources.
The results will be reported as another instalment of Deliverable D5.4, where the paper (Gauer, 2018c) constitutes the first instalment.

7.3 Budget 2019

At the time of writing, the raise of the funding from 3 MNOK to 4 MNOK, stipulated in the proposed National Budget, has not been officially confirmed. The project budget shown in Table 4 presents two alternatives, with the numbers in the third and fourth column valid for unchanged and increased funding level, respectively.

Table 4 Revised list of tasks and allocated budget for 2018. The fourth column assumes that the total budget will be increased to 4 MNOK, the third column represents a fall-back budget if the increase were to be revoked

Task	Task description	Budget (kNOK)	
T0.1	Administration, meetings	80	100
T0.2	Advisory group	100	100
T0.3	Conferences and publications	50	250
T0.4	Reporting	100	100
T0.5	Dissemination	150	150
T0.6	Project proposal 2020–2022	100	100
	Total WP 0	**550**	**800**
T1.1	Running expenditures Fonnbu	150	150
T1.2	Maintenance Ryggfonn, Gudvangen	350	600
T1.3	Experiments Ryggfonn, Gudvangen	300	400
T1.4	Data analysis Ryggfonn, Gudvangen	200	200
T1.5	Model development	200	250
	Total WP 1	**1200**	**1600**
T2.1	Testing and deployment of StatPack	200	200
T2.2	Impact of mitigation measures on land-use planning	200	200
	Total WP 2	**400**	**400**
T3.1	Snow cover simulation	150	200
T3.2	Methodology for slushflow forecasting	50	50
T3.4	Circum-Arctic Slushflow Network	50	50
	Total WP 3	**250**	**300**
T4.1	Avalanche observations	200	200
T4.2	Avalanche detection by infrasound	200	200
	Total WP 4	**400**	**400**
T5.1	Wind fields in the mountains	200	250
T5.3	Avalanche release probability	0	250
	Total WP 5	**200**	**500**
	Total FoU Snøskred 2017–2019 in 2019	**3000**	**4000**

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Kontroll- og referanseside/ Review and reference page

Dokumentinformasjon/*Document information*		
Dokumenttittel/*Document title* Annual Report 2018		**Dokumentnr./*Document no.*** 20170131-11-R
Dokumenttype/*Type of document* Rapport / Report	**Oppdragsgiver/*Client*** Norges vassdrags- og energidirektorat (NVE)	**Dato/*Date*** 2018-12-21
Rettigheter til dokumentet iht kontrakt/ *Proprietary rights to the document according to contract* Oppdragsgiver / Client		**Rev.nr.&dato/*Rev.no.&date*** 0 /
Distribusjon/*Distribution* ÅPEN: Skal tilgjengeliggjøres i åpent arkiv (BRAGE) / OPEN: To be published in open archives (BRAGE)		
Emneord/*Keywords* Snow avalanches, full-scale experiments, field observations, dynamical and statistical models, slushflows, snowdrift		

Stedfesting/*Geographical information*	
Land, fylke/*Country* —	**Havområde/*Offshore area*** —
Kommune/*Municipality* —	**Feltnavn/*Field name*** —
Sted/*Location* —	**Sted/*Location*** —
Kartblad/*Map* —	**Felt, blokknr./*Field, Block No.*** —
UTM-koordinater/*UTM-coordinates* **Zone: —East: —North: —**	**Koordinater/*Coordinates*** **Projection, datum:— East: — North: —**

Dokumentkontroll/*Document control*

Kvalitetssikring i henhold til/*Quality assurance according to NS-EN ISO9001*

Rev/ *Rev.*	**Revisjonsgrunnlag/*Reason for revision***	**Egenkontroll av/ *Self review by:***	**Sidemanns-kontroll av/ *Colleague review by:***	**Uavhengig kontroll av/ *Independent review by:***	**Tverrfaglig kontroll av/ *Interdisciplinary review by:***
0	Original document	2019-01-29 Dieter Issler	2019-03-19 Galina Ragulina		

Dokument godkjent for utsendelse/ *Document approved for release*	**Dato/*Date*** 21 March 2019	**Prosjektleder/*Project Manager*** Dieter Issler

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